Thermospheric/Ionospheric Extension of the Whole Atmosphere Community Climate Model (WACCM-X)

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LONG-TERM GOALS

A key question in space weather and space environment study is to understand and to quantify the contribution to thermospheric/ionospheric variability by processes from both the lower atmosphere and from the magnetosphere and solar input. The primary goal of this project is address this question by developing a model that encompasses the entire atmosphere, from the ground/ocean to the upper thermosphere. We will achieve this goal by extending the NCAR Whole Atmosphere Community Climate Model into the thermosphere and ionosphere (WACCM-X), making use of the physics and many of the algorithms of the National Center for Atmospheric Research Thermosphere-Ionosphere-Mesosphere-Electrodynamics General-Circulation Model (NCAR TIME-GCM). Such a seamless whole atmosphere model will enable us to self-consistently study how elements in the coupled upper atmosphere/ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the complex interactions between the lower atmosphere/ocean and the middle and upper atmosphere. The information from this research will be useful for ONR to develop a seamless operational model that simulates the present day structure and dynamics of the thermosphere-ionosphere-mesosphere-lower atmosphere-system including its response to solar variability and global change.

OBJECTIVES

Our scientific objectives are to study the nature of the sources of variability in the upper atmosphere/ionosphere system self-consistently using a seamless model spanning the whole atmosphere. The primary technical objectives of the project are: (1) Extend the upward boundary of the WACCM to the top of the thermosphere ($3x10^{-9}$ hPa, around ~500 km) by including the main thermospheric and ionospheric processes. (2) Test and refine the WACCM-X by comparing with empirical models and with observations of upper atmospheric tides, ionospheric electric fields, and geomagnetic perturbations. (3) Help the development of NOGAPS-ALPHA into the lower thermosphere by transferring appropriate packages from WACCM-X. (4) Help the development of ionospheric data assimilation schemes at the Utah State University by providing WACCM-X output with tidal and planetary wave variability.

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14. ABSTRACT
A key question in space weather and space environment study is to understand and to quantify the contribution to thermospheric/ionospheric variability by processes from both the lower atmosphere and from the magnetosphere and solar input. The primary goal of this project is address this question by developing a model that encompasses the entire atmosphere, from the ground/ocean to the upper thermosphere. We will achieve this goal by extending the NCAR Whole Atmosphere Community Climate Model into the thermosphere and ionosphere (WACCM-X), making use of the physics and many of the algorithms of the National Center for Atmospheric Research Thermosphere-IonosphereMesosphere-Electrodynamics General-Circulation Model (NCAR TIME-GCM). Such a seamless whole atmosphere model will enable us to self-consistently study how elements in the coupled upper atmosphere/ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the complex interactions between the lower atmosphere/ocean and the middle and upper atmosphere. The information from this research will be useful for ONR to develop a seamless operational model that simulates the present day structure and dynamics of the thermosphere-ionosphere-mesosphere-lower atmosphere-system including its response to solar variability and global change.

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APPROACH

The WACCM-X is built upon the WACCM version 3 (WACCM3), which is based on the NCAR Community Atmospheric Model (CAM3) and now a component of the Community Climate System Model (CCSM), and includes all the physical parameterizations of that model. There are three dynamical cores available in CAM3, and the finite volume dynamical core [Lin, 2004] has been used for WACCM3. This method is superior for mass conservation and important for the interactive chemistry in WACCM3. The WACCM3/WACCM-X chemistry module is derived from the three-dimensional chemical transport Model for Ozone and Related chemical Tracers (MOZART) [Brasseur et al., 1998], which solves 51 neutral species plus 5 major ion species (O2+, O+, NO+, N+, and N2+) and electron density. Processes important for the energetics in the upper atmosphere, including photolysis in the solar spectral range from the EUV to 750 nm, photoionization, solar heating at short and long wavelengths, including infrared transfer under non-local thermodynamic equilibrium (NLTE) conditions, auroral processes, ion drag, and Joule heating are calculated or parameterized in WACCM3. Gravity wave forcing and eddy diffusion induced by gravity wave breaking are parameterized in WACCM3. Molecular diffusion of minor species diffusion in the vertical direction is also calculated. A detailed summary of WACCM3 can be found in Garcia et al. [2007].

The present upper boundary of WACCM3, at around ~150 km, only permits studies of the thermosphere up to about ~110-120 km, because higher altitudes are significantly affected by the assumed upper boundary conditions. The first phase of this development is to raise the upper boundary of the model to the upper thermosphere and at the same time include the physics that is relevant for the thermosphere. In particular, major species diffusion and species dependent molecular weight, specific heats, and gas constants need to be formulated in WACCM-X, and upper boundary conditions for winds, temperature, and various species appropriate for the upper thermosphere need to be implemented. With these developments, WACCM now has a thermospheric component. The compositional, thermal and wind structures are being validated against empirical model results and TIME-GCM results. The second phase of the development, which is on-going, is to develop ionospheric electrodynamics modules, such as ambipolar diffusion and ExB drift, in WACCM-X.

Also funded by this award, we have further developed the NCAR thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (TIME-GCM) and continued to use the model for studying the upper atmospheric variability. To better resolve the impact of lower atmospheric variability on the upper atmosphere and to take advantage of the augmented computing power afforded by the new NCAR facilities, the spatial resolution of TIME-GCM has been doubled in each dimension, and the lower boundary condition of TIME-GCM can now be specified by assimilated data from the European Centre for Medium-Range Weather Forecast (ECMWF), which has 6-hourly output. This model is now being used to study short-term variability due to planetary waves and gravity waves.

NCAR personnel participating in this work include: Han-Li Liu (dynamics of the middle and upper atmosphere), Raymond Roble (aeronomy and global upper atmosphere and ionospheric dynamics), Arthur Richmond (electrodynamics and upper atmosphere waves), Stanley Solomon (ionospheric physics), Astrid Maute (scientific support on ionospheric physics), Liying Qian (scientific support on thermospheric physics), Joseph McInerney (scientific/programming support: model upward extension), and Benjamin Foster (programming support and model development). WACCM is a collaborative

effort between three NCAR Divisions: The High Altitude Observatory (HAO), The Climate and Global Dynamics Division (CGD), and the Atmospheric Chemistry Division (ACD), and involves scientists from these divisions as well as outside collaborators.

WORK COMPLETED

Extended the WACCM (1.9^ox2.5^o degrees horizontal resolution) to the upper thermosphere at 3.4×10^{-9} hPa (the same as the upper boundary of the TIME-GCM, approximately at 500 km). In the process of achieving this upward extension, we have (1) Implemented modules to resolve the major species diffusion, which becomes increasingly important above 110 km. (2) Implemented modules and revised the codes to reflect the constituent-dependency of the specific heats, gas constant, and mean molecular weight. They were set to constants in the previous codes. (3) Revised the treatment of the vertical diffusion equations for minor species and heat conduction equation.

Made test runs using the extended WACCM over one model year under solar maximum, solar medium, and solar minimum conditions, and obtained the wind structure, thermal structure, the vertical profiles of major species (N2, O2, O), oxygen species (O3, O1D, O2_1S, O2_1D), hydrogen species (H, H2O, HO2, OH), nitrogen species (NO, NO2), carbon species (CO, CO2, CH4), ions (O+, O2+, NO+, N+, N2+) and electron density from the ground to the upper thermosphere.

Made comparisons with TIME-GCM and MSIS/HWM and the wind/temperature/compositional structures in the middle and upper atmosphere are in good agreement with those obtained from TIME-GCM and MSIS/HWM. This is the first time that the wind, temperature and compositional structures are resolved from the ground to the upper thermosphere self-consistently in a seamless model.

Compared the thermospheric density under solar maximum, medium, and minimum conditions from WACCM-X simulations with MSIS. WACCM-X successfully reproduced the semi-annual variation of the O/N2 ratio, with both the magnitude and phase in good agreement with MSIS.

Compared both migrating and non-migrating tides from WACCM-X with NASA TIMED/SABER and TIDI observations. The seasonal variation of these tides from the model is in good agreement with that from the observations. The thermospheric tides from the model also show strong short-term variability.

Migrated WACCM3/WACCM-X into the CCSM framework, so that the models can now run with interactive ocean models in addition to specified Sea Surface Temperature.

Developed and tested a high resolution version of TIME-GCM (2.5^ox2.5^ox0.25 scale height) with the lower boundary specified by the ECMWF operational model results at 10 hPa (2.5^ox2.5^o and 6-hourly output). Initial simulation shows that the tidal variability and non-migration tides are better resolved.

The upper boundary of the TIE-GCM, TIME-GCM and WACCM-X are at approximately 500 km altitude. To self-consistently model the ion flux and ionospheric electrodynamics we need to include a model of the plasmasphere. For this purpose, we have coupled the Global Ionosphere Plasmasphere Model (GIP) with TIE-GCM by collaborating with George Millward from the NOAA Space Weather Prediction Center. The modular approach in coupling the TIE-GCM and GIP makes it straightforward to couple WACCM and GIP in the next phase of development. The coupled code is still undergoing testing of all the interfaces and coupling modes. Immediate future work will include comparing the

results of the coupled GIP-TIEGCM code with the stand-alone TIE-GCM and GIP models to verify the improvements.

Further development of TGCM/WACCM postprocessors: (1) Further developed the TGCM IDL postprocessor so that it can process results from the extended WACCM simulations. (2) Further developed the TGCM FORTRAN postprocessor so that it can process results from the high resolution version of TIME-GCM.

Provided the Naval Research Laboratory Navy Operational Global Atmospheric Prediction System Advanced Level Physics-High Altitude (NRL NOGAPS-ALPHA) team with an upgraded version of the Global Mean Model and the WACCM FUV module.

Provided the Utah State University Global Assimilation of Ionospheric Measurements (USU GAIM) team with WACCM output for studying ionospheric data assimilation in the presence of variability due to lower atmosphere perturbations (tides, planetary waves, and gravity waves).

Organized a CEDAR workshop, Ground-Space Models for Studying Atmospheric Coupling (Co-Chairs: Han-Li Liu, Dave Siskind and Bob Schunk, 18 June, 2008, Zermatt Resort, Midway, Utah http://cedarweb.hao.ucar.edu/wiki/index.php/2008_Workshop:Ground-Space_Models_for_Studying_Atmospheric_Coupling). The two-session workshop was intended to review the current status of such models and to discuss model development, validation, model inter-comparison, research application of these models, and integration with the CEDAR observational community.

RESULTS

Figure 1 shows the meridional winds at March equinox from WACCM-X (top), HWM (middle), and TIE-GCM (bottom) at 2.7×10^{-5} hPa (~120 km, left) and 6.8×10^{-8} hPa (~330 km, right) under solar maximum conditions. The longitude structures and the diurnal variation of the meridional wind in the upper thermosphere from all three models are in general agreement, and the wind from WACCM-X shows more variability. At lower thermosphere, winds from all three models show semi-diurnal tidal structures with comparable phase and amplitude. In addition, the WACCM-X wind has a clear wavenumber 3 (DE3) signature at lower latitudes, indicating the presence of diurnal eastward 3 non-migrating tide in WACCM-X. Figure 2 compares the DE3 temperature and wind components to those measured by the TIMED/SABER [Garcia and Liebermann, 2007] and TIDI [Wu et al., 2008]. Both the amplitude and seasonal variation of these components compare very well between the model results and the observations.

Figure 3 is the zonal wind in the altitude range between the ground and the upper thermosphere from WACCM-X. The plot clearly shows different features from lower to upper atmosphere: below the mesosphere the time scale is dominated by planetary waves, in the upper thermosphere by the migrating tides, and in between the temporal and spatial scales are very complex, involving planetary waves, tides, gravity waves and interactions of these components.

Satellite drag data show that there are annual and semi-annual changes of thermospheric density, which is not well resolved in WACCM or TIME-GCM. Using TIE-GCM, Qian et al. found that a seasonal variation of eddy diffusion compatible is needed to obtain the density variation based on model

sensitivity studies and satellite drag data. Simulations show that when the eddy diffusion with seasonal variation is imposed at the lower boundary of the TIE-GCM, neutral density variation consistent with satellite drag data and column O/N2 variation consistent with measurements by TIMED/GUVI are obtained. These model-data comparisons and analyses indicate that turbulent mixing, which is primarily related to gravity waves from the lower atmosphere, may contribute to seasonal variation in the thermosphere, particularly the asymmetry between solstices that cannot be explained by other mechanisms. (Qian, L., S. C. Solomon, and T. J. Kane, Seasonal variation of thermospheric density in response to forcing by the lower atmosphere, *J. Geophys. Res.*, submitted, 2008.)

Liu et al. used WACCM to examine the chaotic error growth in the whole atmosphere context, which will help us better understand the predictability of the whole atmosphere system and future application of data assimilation to forecasting the system. From ensemble WACCM simulations, they found that the early growth of differences in initial conditions are associated with gravity waves, this becomes apparent first in the upper atmosphere and progresses downward. The differences later become more profound on increasingly larger scales, and the growth rates of the differences change in various atmospheric regions and with seasons, and correspond closely with the strength of planetary waves. The growth rates, on the other hand, are not sensitive to the altitude where the small differences are introduced in the initial conditions or the physical nature of the differences. Furthermore, the growth rates in the middle and upper atmosphere are significantly reduced if the lower atmosphere is regularly reinitialized, and the reduction depends on the frequency and the altitude range of the re-initialization. (Liu, H.-L., F. Sassi, and R. R. Garcia, Error growth in a whole atmosphere climate model, *J. Atmos. Sci.*, in press, 2008.)

Deng et al. examined the non-hydrostatic effect on the upper atmosphere by comparing results from the Global Ionosphere and Thermosphere Model (GITM) and TIME-GCM. Their results show that after a sudden intense enhancement of high-latitude Joule heating, the vertical pressure gradient force can locally be 25% larger than gravity, resulting in a significant disturbance away from hydrostatic equilibrium. This disturbance is transported from the lower altitude source region to high altitudes by an acoustic wave, which has been simulated in a global circulation model for the first time. Due to the conservation of perturbation energy, the magnitude of the vertical wind perturbation increases with altitude and reaches 150 (250) m/s at 300 (430) km during the disturbance. The upward neutral wind lifts the atmosphere and raises the neutral density at high altitudes by more than 100%. These large vertical winds are not typically reproduced by hydrostatic models of the thermosphere and ionosphere. The results give an explanation to the cause of such strong vertical winds reported in previous observations. (Deng, Y., A. D. Richmond, A. J. Ridley, and H.-L. Liu, Assessment of the non-hydrostatic effect on the upper atmosphere using a general circulation model (GCM), *Geophys. Res. Lett*., 35, L01104, 10.1029/2007GL032182, 2008.)

Using simulation results from WACCM, Liu et al. revisited the wind balance in the mesosphere and lower thermosphere and demonstrated that the geostrophic balance approximate holds in the meridional direction but is no longer valid in the zonal direction due to the large zonal gravity wave forcing. As a result, the zonal mean geostrophic meridional wind is significantly different from the actual zonal mean meridional wind, and the residual mean merdional circulation derived from geostrophic winds is much weaker than that derived from model winds. The ageostrophic contribution comes primarily from gravity wave forcing, so that there is an approximate three-way balance between pressure gradient, Coriolis force, and gravity wave forcing. The relationship between the geostrophic winds and actual winds is also tested using measurements from TIMED SABER and TIDI instruments.

This research provides a possible route to directly infer gravity wave forcing from meridional wind measurements. (H.-L. Liu, D. R. Marsh, Q. Wu, and J. Xu, Wind balance in the mesosphere and lower thermosphere, in preparation.)

Yuan et al. used multiple years of continuous observations of mesopause temperature and horizontal wind, each lasting longer than 24 hours, from Colorado State University Na Lidar Facility Fort Collins, CO (41°N, 105°W) to derive monthly climatology and seasonal variations of temperature and horizontal winds. The observed mean-state in temperature, zonal and meridional winds are compared with the predictions of 3 current general circulation models: WACCM3, the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA), and the year 2003 simulation of the TIME-GCM. While general agreement is found between observation and model predictions, there exist discrepancies between model prediction and observation, as well as among predictions from different models. The altitude of winter zonal wind reversal and seasonal asymmetry of the pole-to-pole meridional flow are also compared, with the importance of full-diurnal–cycle observation for the determination of mean states studied. (T. Yuan, C.-Y. She, D. A. Krueger, F. Sassi, R. R. Garcia, R. G. Roble, H.-L. Liu, and H. Schmidt, Climatology of mesopause region temperature, zonal wind and meridional wind over Fort Collins, CO (41ºN, 105ºW) and comparison with model simulations, *J. Geophys. Res.*,113, D03105, 2008.)

Marsh et al. used WACCM3 to study the atmospheric response from the surface to the lower thermosphere to changes in solar and geomagnetic forcing over the 11-year solar cycle. Energy inputs include solar radiation and energetic particles, which vary significantly over the solar cycle. This paper presents a comparison of simulations for solar cycle maximum and solar cycle minimum conditions. Changes in composition and dynamical variables are clearly seen in the middle and upper atmosphere, and these in turn affect the terms in the energy budget. Generally good agreement is found between the model response and that derived from satellite observations. A small but statistically significant response is predicted in tropospheric winds and temperatures which is consistent with signal observed in reanalysis data sets. (Marsh, D. R., R. R. Garcia, D. E. Kinnison, B. A. Boville, K. Matthes, F. Sassi, and S. C. Solomon. Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing. *J. Geophys. Res*., 112, D23306, 2007.)

Liu studied the large wind shear and fast transport above the mesopause and possible relationship with gravity waves and tides. With the maximum atmospheric static stability above the mesopause, large wind shears can be obtained under the limit of dynamic stability and the consistently large observed wind shears there can thus be related to the stability constraint set by the background atmosphere. The maximum wind shears determined from this stability limit are found to be in general agreement with the outer envelope of most of the large wind shears from chemical release experiments at low and mid-latitudes. Diagnostic calculations also indicate that the meridional transport in this region may not be well understood solely by examining the mean meridional circulation, and large amplitude tides/planetary waves can play an important role in the bulk transport of tracers. Strong stochastic winds, presumably due to gravity waves, do not seem to significantly change the large scale pattern of the transport but may extend the range of the tracer movement. (Liu, H.-L., On the large wind shear and fast meridional transport above the mesopause, *Geophys. Res. Lett.*, 34, L08815, doi:10.1029/2006GL028789, 2007.)

Liu et al. studied the large mesospheric temperature inversion and coincident strong short-term tidal variability using temperature and wind measurements from lidar, NASA TIMED/SABER and TIDI

instruments and compare these results with TIME-GCM. With a large transient planetary wave specified at the model lower boundary, the model is able to produce strong diurnal tidal variability comparable to that from the lidar observation, and the modeled temperature inversion is similar to that from the SABER measurement. The model results suggest that the planetary/tidal wave interaction excites non-migrating tides and modulates the gravity modes and/or the rotational modes of the diurnal migrating tide. Among the non-migrating tides, the diurnal zonally symmetric (S=0) component is the strongest, and its interaction with the planetary wave leads to a strong diurnal eastward wavenumber 1 component. (Liu, H.-L., T. Li, C.-Y. She, J. Oberheide, Q. Wu, M. E. Hagan, J. Xu, R. G. Roble, M. G. Mlynczak, J. M. Russell III, Comparative study of short term tidal variability, *J. Geophys. Res.*, 112, doi:10.1029/2007JD008542, 2007.)

IMPACT/APPLICATIONS

WACCM, TIE-GCM, and TIME-GCM are community models and the development, evaluation and application of these models have and still will have extensive community involvement. The WACCM3 has been recently released (http://waccm.acd.ucar.edu/) and can be downloaded from the NCAR data portal (http://cdp.ucar.edu/). The TIE-GCM will soon be released through the Community Coordinated Modeling Center (CCMC). In addition, we participate in NRL studies, NSF Coupling and Energetics of Atmospheric Regions (CEDAR), and Space Weather Initiative (SWI) programs. We worked closely with NASA TIMED team to help interpret the observational results, and a NASA Small Explorer team for mission planning. The WACCM provides a seamless modeling tool to study whole atmosphere coupling and connecting the tropospheric climate with space weather, and it attracts participation from the lower, middle and upper atmosphere communities. We also participate in the NCAR Climate Systems Modeling effort in examining the couplings between the upper and lower atmospheres and in an attempt to understand the effects of the variable solar outputs on the coupled Earth system. We also work closely with other seamless modeling teams, such at the NRL NOGAPS-ALPHA team.

RELATED PROJECTS

The numerical modeling effort is complemented by a data analysis and interpretation efforts, and comparative studies with observations and other model development. We have actively participated or have participation from the following projects/missions:

NASA TIMED Satellite Mission.
NASA Living With a Star Program.
NASA Geospace SR&T Program.
NSF CEDAR: Whole-Atmosphere Modeling of the Thermosphere/Ionosphere Responses to Lower-Atmosphere Dynamics and Variability.
NSF Lidar Consortium.
NCAR Community Climate System Model.
NRL NOGAPS-ALPHA.
USU GAIM.

REFERENCES

Brasseur, G. P., D. A. Hauglustaine, S. Walters, P. J. Rasch, J. F. Muller, C. Granier, and X. X. Tie, MOZART, a global chemical transport model for ozone and related chemical tracers 1. Model description, *J. Geophys. Res*., 103, 28265-28289, 1998.

Garcia, R. R., and R. S. Lieberman, Short-period waves in the equatorial middle atmosphere, International Symposium on Coupling Processes in the Equatorial Atmosphere, Kyoto, Japan, 20-23 March, 2007.

Garcia, R. R., D. R. Marsh, D. E. Kinnison, B. A. Boville, and F. Sassi, Simulation of secular trends in the middle atmosphere, 1950-2003, *J. Geophys. Res*., 112, Art. No. D09301, 2007.

Lin, S.-J., A "vertically Lagrangian" finite-volume dynamical core for global models, *Mon. Weather Rev., 132*, 2293-2307, 2004.

Wu, Q., D. A. Ortland, T. L. Kileen, R. G. Roble, M. E. Hagan, H.-L.Liu, S. C. Solomon, J. Xu, W. R. Skinner, R. J. Niciejewski, Global distribution and inter-annual variation of mesospheric and lower thermospheric neutral wind diurnal tide, Part 2: non-migrating tide, *J. Geophys. Res*., 113, A05309, 10.1029/2007JA012543, 2008.

PUBLICATIONS

Burns, A. G., W. Wang, T. L. Killeen, S. C. Solomon, and M. Wiltberger, Vertical variations in the N2 mass mixing ratio during a thermospheric storm that have been simulated using a coupled magnetosphere-ionosphere-thermosphere model. *J. Geophys. Res., 111, A11309,* doi:10.1029/2006JA011746, 2006. [published]

Chang, L. C., S. E. Palo, and H.-L. Liu, Short-term Variation of the s=1 Nonmigrating 1 Semidiurnal Tide During the 2002 Sudden 2 Stratospheric Warming, *J. Geophys. Res*., submitted, 2008.

Chu, X., C. Yamashita, P. J. Espy, G. J. Nott, E. J. Jensen, H.-L. Liu, W. Huang, and J. P. Thayer, Responses of Polar Mesospheric Cloud Brightness to Stratospheric Gravity Waves at the South Pole and Rothera, Antarctica, *J. Atmos. Solar Terr. Phys*, submitted, 2008.

Deng, Y., A. D. Richmond, A. J. Ridley, and H.-L. Liu, Assessment of the non-hydrostatic effect on the upper atmosphere using a general circulation model (GCM), *Geophys. Res. Lett*., 35, L01104, doi:10.1029/2007GL032182, 2008. [published]

Fritts, D. C, M. A. Abdu, B. R. Batista, I. S. Batista, P. P. Batista, R. Buriti, B. R. Clemesha, J. Comberiate, T. Dautermann, E. de Paula, B. J. Fechine, B. Fejer, D. Gobbi, J. Haase, F. Kamalabadi, B. Laughman, P. P. Lima, H.-L. Liu, A. Medeiros, D. Pautet, F. Sao Sabbas, J. H. A. Sobral, P. Stamus, H. Takahashi, M. J. Taylor, S. L. Vadas, and C. Wrasse, The Spread F Experiment (SpreadFEx): Program overview and first results, *Earth, Planets and Space*, in press, 2008. [in press]

Fritts, D. C, M. A. Abdu, B. R. Batista, I. S. Batista, P. P. Batista, R. Buriti, B. R. Clemesha, J. Comberiate, T. Dautermann, E. de Paula, B. J. Fechine, B. Fejer, D. Gobbi, J. Haase, F. Kamalabadi, B. Laughman, P. P. Lima, H.-L. Liu, A. Medeiros, D. Pautet, F. Sao Sabbas, J. H. A. Sobral, P. Stamus, H. Takahashi, M. J. Taylor, S. L. Vadas, and C. Wrasse, Overview and summary of the Spread F Experiment (SpreadFEx), *Ann. Geophys*., in press, 2008. [in press]

Fritts, D. C, S. L Vadas, D. M. Riggin, M. A. Abdu, I. S. Batista, H. Takahashi, A. Medeiros, F. Kamalabadi, H.-L. Liu, B. G. Fejer, and M. J. Taylor, Gravity wave and tidal influences on equatorial spread F based on observations during the Spread F Experiment (SpreadFEx), *Ann. Geophys*., in press, 2008. [in press]

Gelinas, L. J., J. H. Hecht, R. L. Walterschied, R. G. Roble, and J. Woithe, A seasonal study of mesospheric temperatures and emission intensities at Adelaide and Alice Springs, *J. Geophys. Res*.,113, A01304, 10.1029/2007JA012587, 2008. [published]

Hagan, M.E., A. Maute, R.G. Roble, A.D. Richmond, T.J. Immel, and S.L. England, The effects of deep tropical clouds on the Earth's ionosphere, *Geophys. Res. Lett*., 20, L20109, 10.1029/2007GL030142, 2007. [published]

Jee, G., A. G. Burns, W. Wang, S. C. Solomon, R. W. Schunk, L. Scherliess, D. C. Thompson, J. J. Sojka, and L. Zhu, Duration of an ionospheric data assimilation initialization of a coupled thermosphere-ionosphere model. *Space Weather*, 5, S01004, doi:10.1029/2006SW000250, 2007. [published]

Jee, G., A.G. Burns, W. Wang, S. C. Solomon, R. W. Schunk, L. Scherliess, D. C. Thompson, J. J. Sojka and L. Zhu. Driving the TING model with GAIM electron densities: ionospheric effects on the thermosphere. *J. Geophys. Res*., 113, A03305, 10.1029/2007JA012580, 2008. [published]

Li, T., C. -Y. She, H.-L. Liu, J. Yue, T. Nakamura, D. A. Krueger, Q. Wu, X. Dou, and S. Wang, Observation of local tidal variability and instability, along with dissipation of diurnal tidal harmonics in the mesopause region over Fort Collins, CO (41N, 105W), *J. Geophys. Res*., submitted, 2008.

Li, T., C.-Y. She, H.-L. Liu, and M. T. Montgomery, Evidence of a gravity wave breaking event and the estimation of the wave characteristics from sodium lidar observation over Fort Collins, CO (41N 105W), *Geophys. Res. Lett.*, 34, L05815, doi:10.1029/2006GL028988, 2007. [published]

Li, T., C.-Y. She, S. E. Palo, Q. Wu, H.-L. Liu, and M. L. Salby, Coordinated Lidar and TIMED observations of the quasi-two-day wave during August 2002-2004 and possible quasi-biennial oscillation influence, in press, *Adv. Space Res*., 41, 1462-1470, 2008. [published]

Li, T., C.-Y. She, H.-L. Liu, T. Leblanc, and I. S. McDermid, Sodium lidar observed strong inertia-gravity wave activities in the mesopause region over Fort Collins, CO (41N, 105W), *J. Geophys. Res*., 112, D22104, 10.1029/2007JD008681, 2007. [published]

Liu, H.-L., F. Sassi, and R. R. Garcia, Error growth in a whole atmosphere climate model, *J. Atmos. Sci*., in press, 2008. [in press]

Liu, H.-L., T. Li, C.-Y. She, J. Oberheide, Q. Wu, M. E. Hagan, J. Xu, R. G. Roble, M. G. Mlynczak, J. M. Russell III, Comparative study of short term tidal variability, *J. Geophys. Res.*, 112, doi:10.1029/2007JD008542, 2007. [published]

Liu, H.-L., Spectral Properties of one-dimensional diffusive systems subject to stochastic forcing, *J. Atmos. Sci.*, 64, 579-593, 2007. [published]

Liu, H.-L., On the large wind shear and fast meridional transport above the mesopause, *Geophys. Res. Lett.*, 34, L08815, doi:10.1029/2006GL028789, 2007. [published]

Marsh, D. R., R. R. Garcia, D. E. Kinnison, B. A. Boville, K. Matthes, F. Sassi, and S. C. Solomon. Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing. *J. Geophys. Res*., 112, D23306, 2007. [published]

Qian, L., S. C. Solomon, and T. J. Kane, Seasonal variation of thermospheric density in response to forcing by the lower atmosphere, *J. Geophys. Res*., submitted, 2008.

Qian L., R. G. Roble, S. C. Solomon, T. J. Kane, Calculated and observed climate change in the thermosphere, and a prediction for solar cycle 24, *Geophys. Res. Lett*., 33, L23705, doi:10.1029/2006GL027185, 2006. [published]

Qian, L., S. C. Solomon, R. G. Roble, B. R. Bowman, and F. A. Marcos. Thermospheric neutral density response to solar forcing. *Adv. Space Res.*42, 926-932, 2007. [published]

Richter, J. H., M. A. Geller, R. R. Garcia, H.-L. Liu, and F. Zhang, Report on the gravity wave retreat, Stratospheric Processes and Their Role in Climate (SPARC) Newsletter, No 28, 26-27, 2007. [published]

Solomon, S. C. Effects of carbon dioxide on the upper atmosphere. *McGraw-Hill 2008 Yearbook of Science and Technology, 107, 2008. [published]*

Tian, F., J. F. Kasting, H.-L. Liu, and R. G. Roble, Hydrodynamic planetary thermosphere model. I: The response of the Earth's thermosphere to extreme solar EUV conditions and the significance of adiabatic cooling, *J. Geophys. Res.*, 113, E05008, 10.1029/2007JE002946, 2008. [published]

Vadas, S. L., M. J. Taylor, D. Pautet, P. A. Stamus, D. C. Fritts, H.-L. Liu, F. Sao Sabbas, V. Thiago, P. Batista, and H. Takahashi, Convection: the likely source of the medium-scale gravity waves observed in the OH airglow layer near Brasilia, Brazil, during the SpreadFEx Campaign, *Ann. Geophys.*, submitted, 2008.

Wang, W., A. G. Burns, M. Wiltberger, S. C. Solomon, and T. L. Killeen. An analysis of neutral wind generated currents during geomagnetic storms. *J. Atmos. Sol. Terr. Phys*., 69, 159, doi:10.1016/j.jastp.2006.06.014, 2007. [published]

Wu, Q., D. A. Ortland, T. L. Kileen, R. G. Roble, M. E. Hagan, H.-L. Liu, S. C. Solomon, J. Xu, W. R. Skinner, R. J. Niciejewski, Global distribution and inter-annual variation of mesospheric and lower thermospheric neutral wind diurnal tide, Part 1: migrating tide, *J. Geophys. Res*., 113, A05308, 10.1029/2007JA012542, 2008. [published]

Wu, Q., D. A. Ortland, T. L. Kileen, R. G. Roble, M. E. Hagan, H.-L.Liu, S. C. Solomon, J. Xu, W. R. Skinner, R. J. Niciejewski, Global distribution and inter-annual variation of mesospheric and lower thermospheric neutral wind diurnal tide, Part 2: non-migrating tide, *J. Geophys. Res*., 113, A05309, 10.1029/2007JA012543, 2008. [published]

Xu, J., H.-L. Liu, W. Yuan, A. K. Smith, R. G. Roble, C. J. Mertens, J. M. Russell III, and M. G. Mlynczak, Mesopause structure from TIMED/SABER observations , *J. Geophys. Res*., 112, D09102, doi:10.1029/2006JD007711, 2007. [published]

Xu, J., A. K. Smith, W. Yuan, H.-L. Liu, Q. Wu, M. G. Mlynczak, and J. M., Russell, III, The global structure and long term variations of zonal mean temperature observed by TIMED/SABER, *J. Geophys. Res*., 112, D24106, 10.1029/2007JD008546, 2007. [published]

Yuan, T., C.-Y. She, D. A. Krueger, F. Sassi, R. R. Garcia, R. G. Roble, H.-L. Liu, and H. Schmidt, Climatology of mesopause region temperature, zonal wind and meridional wind over Fort Collins, CO (41ºN, 105ºW) and comparison with model simulations, *J. Geophys. Res*.,113, D03105, 2008. [published]

Yue, J., S. L. Vadas, C.-Y. She, T. Nakamura, S. C. Reising, H.-L. Liu, P. A. Stamus, D. A. Krueger, W. Lyons, and T. Li, Concentric gravity waves in the mesosphere generated by convective plumes in the lower atmosphere, *J. Geophys. Res.*, submitted, 2008.

Zhao, Y., M. J. Taylor, H.-L. Liu, and R. G. Roble, Seasonal oscillations in mesospheric temperatures at low-latitudes, *J. Atmos. Solar Terr. Phys.*, 69, 2367-2378, 2007. [published]

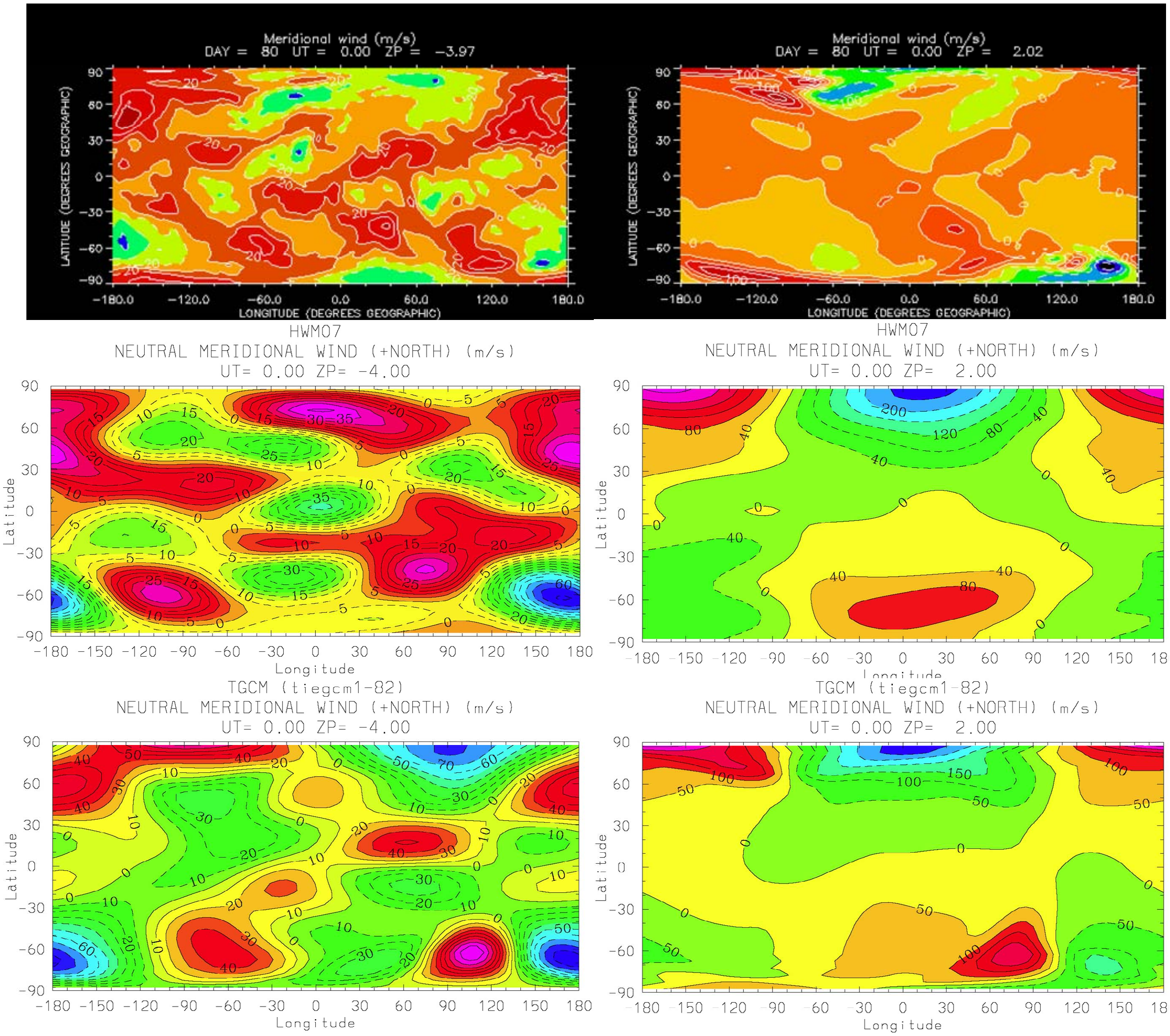

Figure 1: Meridional wind at March equinox from WACCM-X (top), HWM (middle) and TIE-GCM (bottom) at 2.7x10^{-5} hPa (~120 km, left) and 6.8x10^{-8} hPa (~330 km, right) under solar maximum conditions.

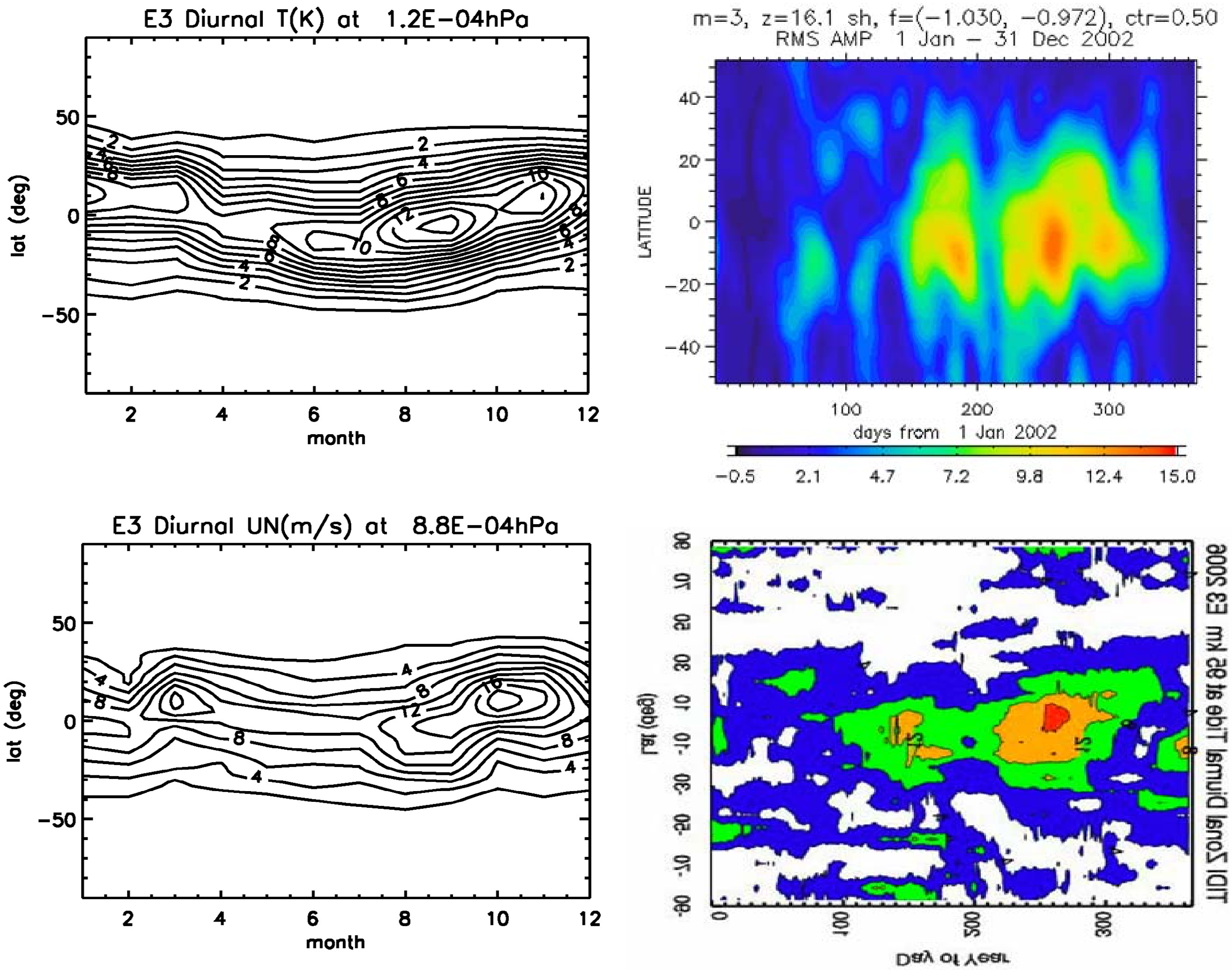

Figure 2: Temperature (top) and zonal wind (bottom) components of diurnal eastward wavenumber 3 (DE3) from WACCM-X (left) and TIMED/SABER (top right) and TIDI (bottom right). The pressure heights of the model results have been chosen to be close to those of SABER and TIDI. The TIDI plot has been rotated to make the layout the same as the other plots.

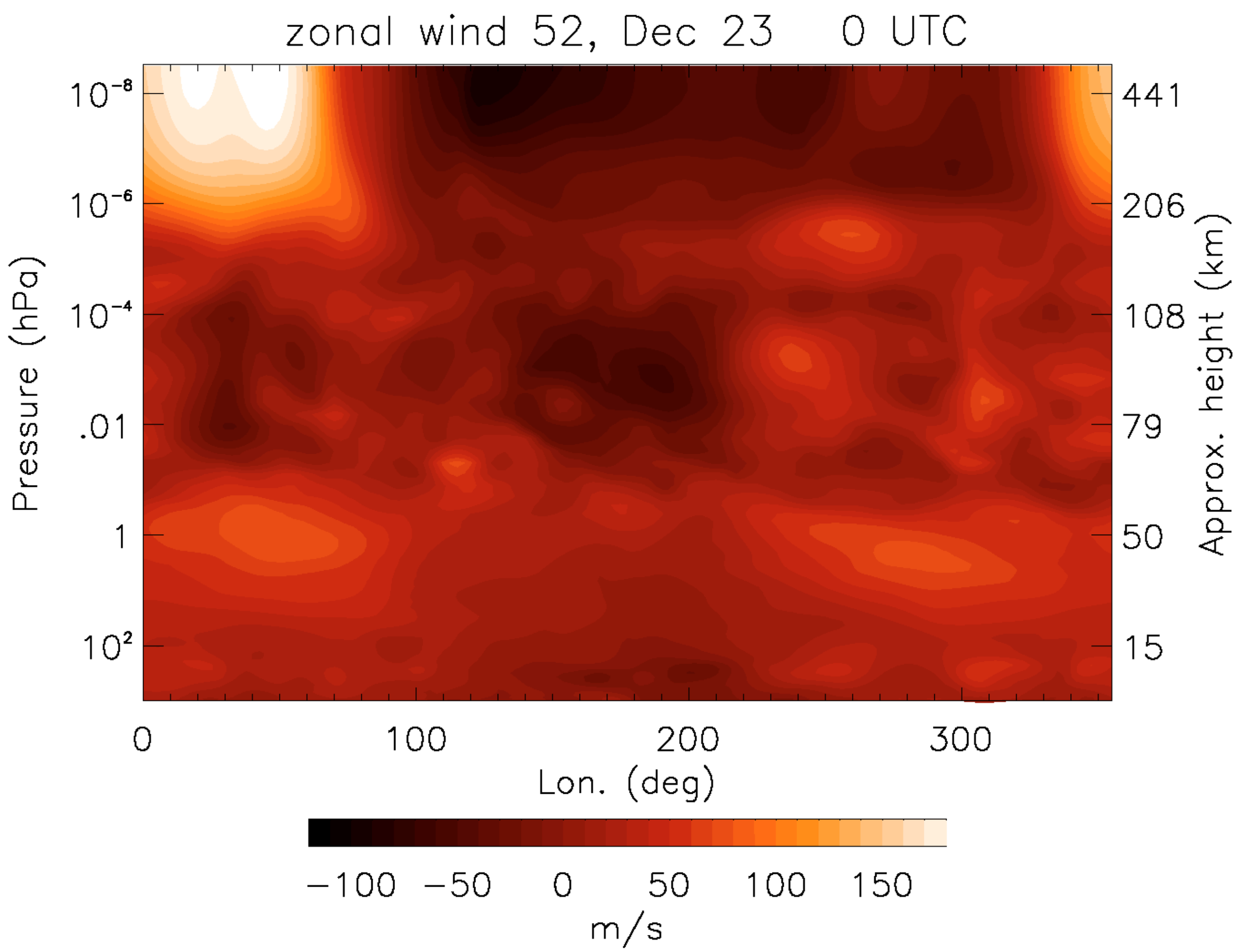

Figure 3: Zonal wind from WACCM-X from the ground to the upper thermosphere at 52N on December 23.